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An Experiment in Transdisciplinary Systems Mapping: Architecture and the Water–Energy–Sanitation Nexus in Brazil

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Abstract: Urban environments contain and are part of a wide range of interconnected complex systems, including infrastructures and services. Rapid and often uncontrolled urbanization triggers distributive inequities and environmental injustices, posing urgent and interconnected challenges that demand inter- and transdisciplinary solutions. Despite architecture's commitment to 'sustainability', its central role in urban systems and their dynamics as well as the discipline's intersections with other disciplines remain relatively little explored. In this contribution, we focus on the water–energy–sanitation (WES) nexus in Brazil, drawing from transdisciplinary workshops, scoping reviews, and systems mapping. We propose a framework for the analysis of urban nexuses. This framework builds on transdisciplinary systems mapping for the identification of nexus components, nodes, and their interconnections. Our findings indicate that a nexus perspective allows us to identify challenges in urban nexuses, productive intersections with the knowledge and approaches from other disciplines, and possible solutions in collaboration with non-academic stakeholders. We advocate for an expanded professional field and a redefined sense of responsibility within the discipline.

Keywords: water–energy–sanitation (WES) nexus; transdisciplinary approach; systems mapping; urban nexus; Brazil; water; energy; sanitation

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1. Introduction

Cities contribute significantly to environmental degradation and climate change [1]. Urban areas, with their high population density and resource consumption, are responsible for 75% of greenhouse gas emissions, driven primarily by transportation demands and stationary energy use [2–4]. The outcomes of rapid and unplanned urbanization in the Global South are manifested in large populations residing in informal settlements facing limited access to essential services, like water, electricity, and sanitation [2]. Structural distributive inequities persist where techno-political barriers hinder infrastructure investments for vulnerable urban populations [5]. In countries like Brazil, economic growth models often prioritize development over environmental quality, exacerbating environmental and social injustices [5–7].

Architecture is implicated in the process of development since architects design the buildings and urban environments within which patterns of everyday life are generated, take place, and aggregate to shape the trajectories of production and consumption, resource use, pollution, and ultimately, social, economic, and environmental change [8]. Despite architecture's stated commitment to addressing long-term sustainability challenges, architectural practice and architecture-related research often appear to perpetuate narrow perspectives, marked by an aversion to engage with matters beyond the confines of the object, building site, or master plan [9–11]. The discipline's apparent failure to recognize architectural interventions as integral elements of larger dynamic systems hinders the development of comprehensive approaches that consider the complex relationships between architecture (as a practice, process, and built form) and its larger contextual frameworks. This lack of recognition becomes particularly consequential when addressing challenges at the intersections of the built form, environmental systems, and socio-economic relations.

Urban systems interlink political, spatial, social, economic, ecological, and cultural systems that interact and exhibit self-organizational behavior [12–14]. Identifying the constituent parts of a defined system and bringing to the fore the diverse relationships among these parts can shed light on the connections between allegedly unrelated matters situated within the existing and emerging urban fabric as well as across various spatial scales [15,16]. An urban nexus denotes a system that encompasses different components with interconnected, often bi-directional relationships across various scales [17,18]. In exploring the interlinkages and interdependencies of different elements within urban systems, nexus approaches provide a comprehensive framework for addressing dynamic water, energy, food, land, climate, society, carbon, and ecosystem challenges. The examined nexuses include the water–energy–food nexus [1], water–energy–fertilizer–food nexus [19], water–energy–food–land nexus [20,21], water–energy–food–land–climate nexus [22], water–food–energy–society nexus [23], water–energy–carbon nexus [24,25], water–land–food nexus [26,27], and water–energy–food–ecosystem nexus [28,29].

Worldwide, 800 million people lack clean water, 1.1 billion lack electricity access, and 2.5 billion lack adequate sanitation [30]. In this paper, we propose an inter- and transdisciplinary focus on the water–energy–sanitation (WES) nexus. The relationships among the elements of this nexus are mutually dependent (Figure 1): water can serve as an energy source; energy enables water treatment and distribution; and water use necessitates sanitation and vice versa [30]. Research that examines the WES nexus through multidisciplinary approaches could inform efforts to develop the 2030 Agenda for Sustainable Development [1] and multiple Sustainable Development Goals (SDGs) [30]. The mechanisms include the design of infrastructural systems aimed at reducing the health risks associated with inadequate infrastructures (SDG3); enhancing water and sanitation availability and management (SDG6); ensuring access to affordable and sustainable energy (SDG 7); improving waste management and resource efficiency (SDG11 and SDG12); and building resilient infrastructures and cities (SDG9 and SDG11) [31].

1.1. Architectural Intersections with the WES Nexus

Each field of expertise has unique perspectives on the constituent elements and dynamics within an urban nexus. However, disciplinary efforts often remain disjointed and reductive and hinder effective communication and the formation of a comprehensive framework that allows for inter- and transdisciplinary collaboration and insights [14,32,33]. In the following paragraphs, we present a brief overview of the research on architecture, where critical knowledge gaps exist with regards to the identification and implementation of appropriate architectural strategies to address water, energy, and sanitation challenges in diverse cultural and socio-economic contexts.

In the broadest sense, scholars in architecture seek to develop design strategies that promote sustainability and resilience in urban environments [34,35]. Within the architectural humanities, research tends to focus on the history and theory of the architecture–environment relationship [36]. Work within the architectural engineering and design fields appears naturally more concerned with the technical aspects of cities and buildings. This includes studies of the impact of urbanization on water resources [37–39], and how architecture and urban design can promote resilience to water scarcity, floods, and droughts [40]. Scholars have also focused on the use of green infrastructure and low-impact development strategies to reduce the impacts of urbanization on water resources, for instance, through greywater systems [41,42], rainwater harvesting [43], and rainwater–greywater recycling [44]. Research on sanitation is focused on the use of green infrastructures, such as rain gardens and bioswales, to treat and manage stormwater [45–48] and the use of decentralized wastewater treatment systems to treat and recycle wastewater [49–51]. These strategies can help to improve water quality and protect public health [52,53].

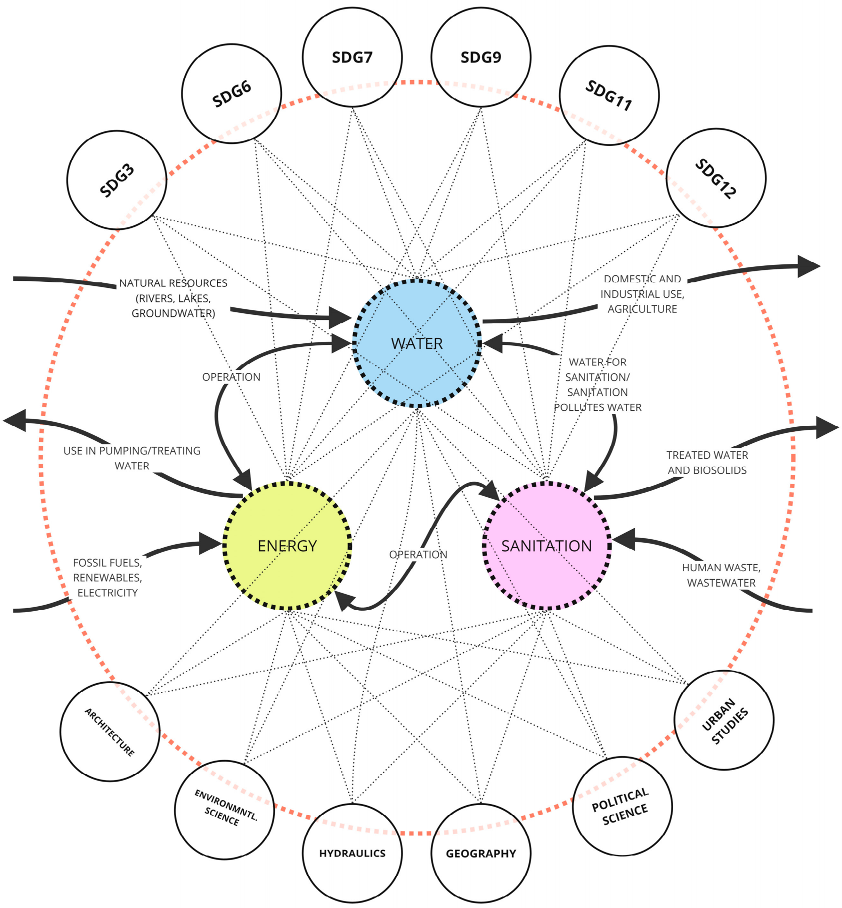

Figure 1. The water–energy–sanitation (WES) nexus and links to SDGs and academic/ professional disciplines.

Finally, there is an abundance of studies that focus on the design of buildings and infrastructures that promote energy-efficient building design [54][1].

However, the labor of translating strategies into practice requires recursive learning that involves interventions that engage society and nature [64]. It also requires knowledge transfer and educational work [65]. Furthermore, while much of the literature focuses on more economically developed countries, the conditions that are typical for less developed countries like Brazil—such as informality in urban environments[2]—can pose a quite diverse set of challenges. Our understanding of this is not well developed. Understanding the technical and environmental aspects of water, energy, and sanitation is helpful and necessary, but the body of work that addresses the interconnections and interdependencies between these systems and their intersection with architecture is extremely limited. How research and design strategies can be developed to address the social and cultural dimensions of the WES nexus requires further study (Table 1).

Table 1. WES nexus intersections with and knowledge gaps in architectural research.

Knowledge Gap	Explanation
Lack of emphasis on interconnections and interdependencies	Limited understanding of the interconnections between water, energy, sanitation, and architecture [34,35].
Limited research on practical implementation and performance evaluation	Insufficient research on implementing and evaluating design strategies in real-world settings [64,65].
Neglect of social and cultural aspects	Inadequate attention to the social and cultural dimensions of the WES nexus [34,35].
Imbalance toward developed countries	Disproportionate focus on developed countries, neglecting the specific challenges faced by developing countries, like Brazil.
Insufficient consideration of broader implications of efficiency	Lack of critical examination of the broader implications of efficiency policies in terms of social, environmental, and economic sustainability [55,61,68].

1.2. Research Scope and Structure

In this paper, our aim is to advance a transdisciplinary[3] perspective to address WES nexus challenges in Brazil. This involves moving beyond traditional disciplinary boundaries and fostering collaboration among experts from diverse fields. We begin by delineating the methodology employed in our study, including a series of transdisciplinary meetings held in 2021 and an interdisciplinary scoping review of the literature on water, energy, and sanitation in Brazil. These activities laid the groundwork for systems mapping aimed at identifying interconnections between the elements of the WES nexus. We ask: how do fragmented governance and management practices across water, energy, and sanitation sectors in Brazil contribute to inefficiencies in addressing challenges within the WES nexus? We examine the implications of the identified interconnections, emphasizing economic, geographic, environmental, and sociological aspects. We close by advocating for a transdisciplinary approach involving specialists from diverse disciplines to effectively address the challenges inherent in the WES nexus.

2. Materials and Methods

The iterative process of transdisciplinary research employs systems mapping as the underlying mechanism for the identification and evaluation of interventions, whereby transdisciplinary workshops act as the main vehicle for knowledge integration and knowledge translation [72]. Figure 2 presents a schematic overview of key elements of transdisciplinary working. Under ideal circumstances, this process includes (a) the collaborative identification between academic and non-academic stakeholders of the project aims and scope; (b) the identification of the relevant knowledge domains and, subsequently, knowledge gaps and needs in theory and practice; (c) the definition of systems boundaries and identification, through systematic literature reviews, of domain elements and their interrelations; (d) the integration of different knowledge domains and findings; and (e) the identification of possible interventions and their sustainability outcomes and trade-offs.

The focus of this paper is primarily on steps (a)–(c) outlined above. We report on the process and outcomes of a series of online transdisciplinary workshops, titled 'Towards Healthy Brazil', conducted between July and December 2021 and involving participants from both Brazil and the United Kingdom. To ensure a transdisciplinary approach to the multifaceted challenges posed by the WES nexus in Brazil, the workshops did not address any specific disciplinary community [69,73,74]. Rather, the 24 participants included senior researchers (mentors) and early career researchers with backgrounds in areas as diverse as architecture, biomedical engineering, demography, economics, environmental engineering, environmental science, geosciences, hydraulics, physics, physical and human geography, political science, sanitation engineering, social engineering, and urban studies. Early career researchers were selected following an open call. The selection criteria comprised: experience and the relevance of the applicant's research focus to the workshop; motivation and contribution to the aims of the workshop; description of the anticipated impact resulting from the participation in the workshop; and ability to disseminate the workshop outcomes.

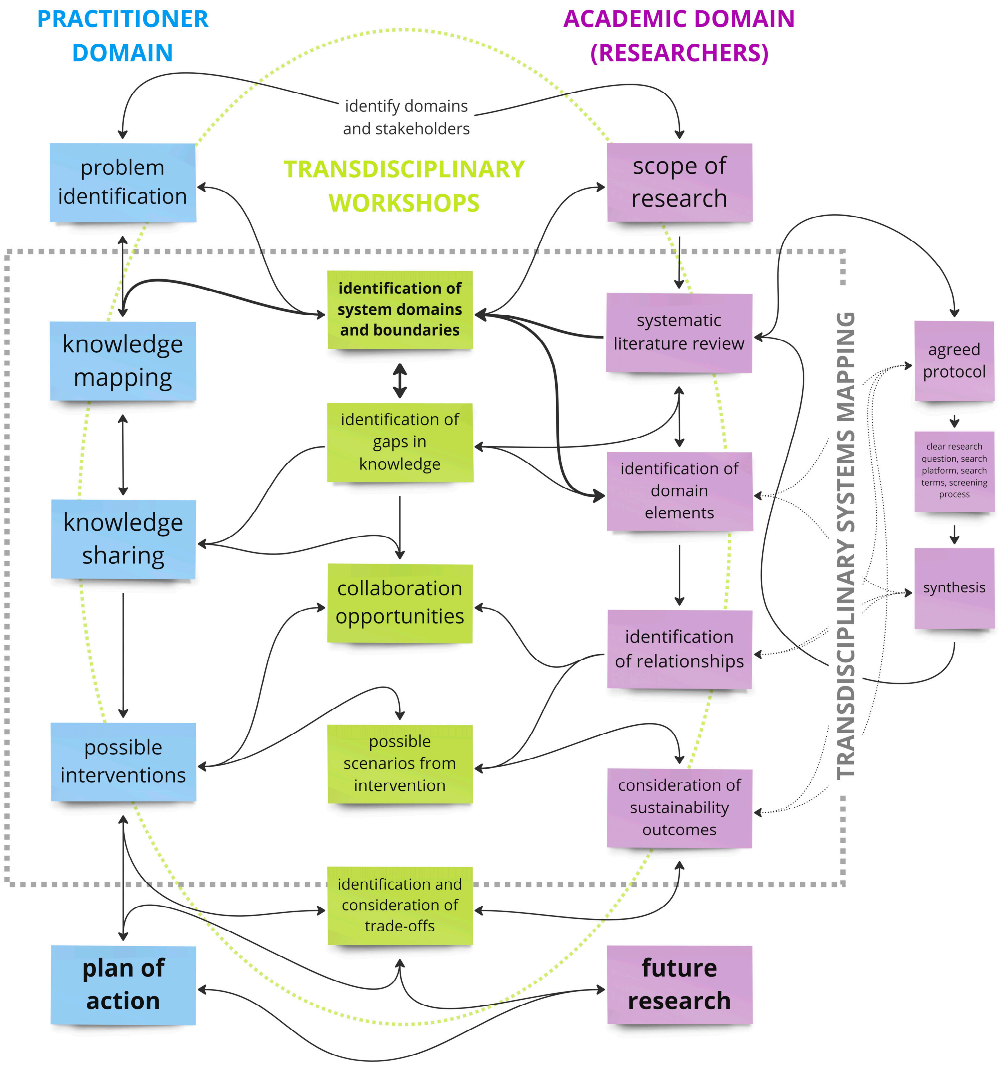

Figure 2. Transdisciplinary systems mapping, including transdisciplinary workshops and systematic literature review.

The first workshop, held over five days, featured introductory sessions, remote keynotes on Global South infrastructuring and urban complexity; case studies of the cities Pereira Barreto, Piracicaba, and São Paulo; and presentations by Brazilian non-academic experts on issues like basic sanitation and the water–energy nexus. Early career researchers benefitted from skills sessions on systems thinking, systems mapping, and urban simulation frameworks designed to build capacity and foster future collaborations toward a better understanding of the WES nexus in Brazil[4].

During follow-on meetings over six months, building on our different disciplinary backgrounds, we conducted an interdisciplinary scoping review of the literature [75], focusing thematically on the three components of water, energy, and sanitation and geographically on the context of Brazil. We employed systems mapping, an analytical approach involving the dissection and visualization of complex adaptive systems to achieve a nuanced understanding of interconnected elements and their relationships [76][5]. Throughout the systems mapping process, a key aspect is the definition of system boundaries as the systems undergo continuous change. It is considered a good approach to start without predefined boundaries so as to minimize the risk of excluding important factors [78]. Researchers can choose to represent specific issues in varying levels of detail, depending on the granularity required, and then simplify the system to enhance clarity for external stakeholders [79][6].

The process of constructing a systems map holds value in itself in that it enables participants to collectively develop insights and seek solutions while mapping the system [80]. In the approach underpinning this research, we employed systems mapping during the literature review and subsequent collaborative workshops to pinpoint a preliminary set of nodes[7] that were associated with each of the three nexus components (water, energy, and sanitation). In some cases, the collaborators projected scenarios based on the literature and challenges identified in the real world. We identified 18 nodes and categorized them according to their type as (T01) infrastructures, encompassing both physical and social elements; (T02) indicators that measure the quality, availability, performance, service coverage, participation in, and/or other aspects of the component(s); (T03) policies, representing policies associated with each nexus component; (T04) actors, including stakeholders ranging from citizens to organizations across public and private sectors; and (T05) aspects/impacts, where 'aspects' are defined as the elements of any organization's activities, products, or services that can interact with the environment (e.g., water use) and 'impacts' are defined as the positive or negative outcomes resulting from these interactions (e.g., groundwater depletion) [81]. We identified and focused on a small set of pairs of nodes and their relationships and used diagramming to represent the interconnections between the nodes within the three-component framework visually.

3. WES Nexus Challenges in Brazil

Water plays a central role in the operation of energy sources, drinking water supply, and transport infrastructure in Brazil. The country has historically relied on hydropower generated by large plants with extensive reservoirs since the 1960s [82]. Hydropower was expected to accelerate the country's urbanization and modernization and, therefore, was favored consistently over time, regardless of the political ideology of the governing administrations. The significant dominance of hydroelectricity in Brazil's power generation matrix, accounting for 64% of the total electric generation [83], highlights the immense political power of the component. Local administrations and producers face significant political, economic, and technical challenges in the governance of water that result from administrative boundaries. River basins and watersheds are often subject to political disputes over access due to the classification of water as a scarce resource and economic commodity [84].

In Brazil, the Basic Sanitation Legal Framework mandates the provision of four essential services to the population: water treatment and distribution, sewage collection and treatment, waste management, and stormwater management. The treatment of sewage is still inadequate, with only 51.2% of the generated sewage being treated [82]. Many municipalities either do not treat sewage or only provide a partial treatment [85,86], resulting in the direct discharge of untreated sewage into rivers. Solid waste management remains a significant challenge, too, with 24.9% of the generated waste still being disposed of in dumpsites [87]. This practice leads to various negative impacts, including the contamination of underground water sources. Additionally, littering in urban areas not only pollutes water systems but also obstructs drains and pipes, posing a threat to both water and energy systems. In addition, the stagnant water resulting from littering becomes a breeding ground for mosquitoes [88,89]. While Brazilian policies have addressed water, sanitation, waste management and stormwater management collectively as basic sanitation services [90–92], the complex nature of the WES nexus is not adequately reflected in the structure of public management, decision-making processes, or the national priority agenda for human rights.

The operational and infrastructural disjunctions between the water, energy, and sanitation sectors in Brazil are manifested across various entities at different levels of government.

These entities include the National Water and Sanitation Agency (ANA), basin committees, the National Agency of Electric Energy (ANEEL), the National Electric System Operator (ONS), environmental agencies, and local/regional supply services. However, these entities operate within distinct deliberative, technical, and operational boundaries, indicating a compartmentalized and non-dialogic approach to public institutional rationality. Disconnected public policies emerge, exacerbating the challenges faced by citizens in their daily lives [93]. For instance, approximately 90% of emergency declarations by municipalities in 2003–2018 in Brazil were attributed to water management issues, including scarcity (droughts) and excess (floods). If water levels are too high or too low, energy and sanitation operations can be compromised. Such issues are closely interconnected with local socio-economic and sanitation dynamics [94].

In Brazil, investments in water, energy, and sanitation infrastructures often prioritize economic profitability over citizen service [95]. Water and sanitation services are often consolidated within the same company, either at the state or municipal level. However, when these companies open their capital to the market, as exemplified by SABESP in the state of São Paulo, there is a tendency to prioritize shareholders' interests and distribute profits to them. Consequently, there is a corporate insensitivity to the difficulties faced by consumers, such as the simultaneous economic and environmental crisis that resulted in water scarcity and increased service prices during the 2014–2015 water crisis and economic recession in São Paulo [96]. This underscores that the issue at hand encompasses not only environmental and technical dimensions but also political, economic, and social aspects that must be taken into account when integrating public policies to prevent similar crises in the future.

As t is evident, interconnections among water, energy, and sanitation arise from Brazil's historical reliance on hydropower, among other factors. However, disjointed governance and management across these sectors have led to inefficiencies. The practical implementation of technically sound solutions, tested under controlled conditions, is influenced by operational, managerial, economic, and cultural factors that ultimately determine their effectiveness [97]. Therefore, the effectiveness of the applied solutions is enhanced when hybrid and interdisciplinary approaches are employed to consider different perspectives [97]. In the following paragraphs, we examine a small sub-set of interconnections to demonstrate the usefulness of the WES nexus approach.

4. Mapping the WES Nexus: Nodes and Their Interconnections

We identified eighteen nodes encompassing infrastructures, indicators, policies, actors, and aspects/impacts. The relationships among these nodes, as illustrated in Table 2 and Figure 3, provide valuable insights into the dynamics of the WES nexus. We began with a scenario that allowed us to think thorough the interconnections between the water, energy, and sanitation components and their infrastructures—but also the multiple disciplinary knowledge and perspectives that can be deployed to understand and address the challenges from these interconnections. The envisaged scenario portrays a precarious situation where regions proximate to a reservoir may face a scarcity of accessible water for diverse purposes (N01), while downstream territories face infrastructure damage and destruction due to the abrupt release of water following the collapse of a dam (N04). Among other possible negative impacts, such a scenario is likely to have significant financial implications, including the cost of obtaining alternative water supplies in order to ensure the availability of drinking water for communities in the vicinity of the reservoir in the short term, as well as the cost of repairing damaged infrastructure and compensating for assets lost [98]. Research in architecture could contribute significantly to this domain, exploring cost-effective strategies and policies for reconstruction and retrofitting structures to minimize economic losses.

Table 2. Examples of nodes and their relationships within the WES nexus. Nodes: N01: Availability; N02: Catchment; N03: Consumers; N04: Dam collapse; N05: Demands; N06: Diseases; N07: Effluent; N08: Floods; N09: Innovation; N10: Interruptions; N11: Land use; N12: Monitoring; N13: Power plants; N14: Privatization; N15: Production; N16: Quality; N17: System resilience; N18: Treatment plants. Sectors: W: Water; E: Energy; S: Sanitation. Types: T01: Infrastructure; T02: Indicators; T03: Policies; T04: Actors; T05: Aspects/Impacts.

Link	Node1	Sector1	Type1	Node2	Sector2	Type2	Reference
L01	N08	W	T05	N04	E	T05	[99]
L02	N12	W	T01	N17	E	T05	[98]
L03	N16	W	T02	N10	E	T02	[100]
L04	N01	W	T02	N15	E	T02	[101]
L05	N16	W	T02	N06	S	T05	[102]
L06	N16	W	T02	N02	W	T02	[103]
L07	N02	W	T01	N01	W	T02	[104,105]
L08	N13	E	T01	N11	E	T05	[106,107]
L09	N04	E	T05	N01	W	T02	[98]
L10	N15	E	T02	N16	W	T02	[108]
L11	N18	S	T01	N05	E	T05	[109]
L12	N09	S	T01	N15	E	T02	[110]
L13	N14	S	T03	N03	S	T04	[87]
L14	N07	S	T05	N16	W	T02	[111]

The above scenario shows that conflicts over water can arise not only from water scarcity, but also from the abundance of water. The unequal distribution of water can result in supply inequalities and social tensions [105]. This context prompts a pertinent exploration within the realm of spatial research—the dynamics within the water component, specifically examining the interconnection between the levels of water availability (N01) and water catchment infrastructures (N02). A geographic analysis would consider how different water uses and functions are integrated within a catchment area, a socio-political construct also referred to as a watershed [104]. Such an analysis could look at infrastructural interconnections and human–infrastructure interactions across multiple spatial, political, economic, and social scales [112].

In the sanitation component, infrastructure innovation (N09) is tied to the current and potential metrics of energy generation (N15). Wastewater treatment plants, although critical for maintaining water quality and availability, account for approximately 1% of the global energy consumption [109]. Recent research in waste management has examined the exploitation of human feces for energy generation [113–115]. Research into the potential of urban systems to harness the energy content of human waste and the development of innovative solutions in sanitation—including within architecture and the built environment—could help to prevent the release of greenhouse gases into the atmosphere while simultaneously enabling the generation of energy.

The relationship between power generation in the energy component (N15) and the indicators of water quality (N16) in the water component has proven to be overly sensitive to global and local power imbalances among social groups with diverse ways of life. It is particularly pronounced in countries where hydropower plays a significant role in the energy mix. For instance, artisanal fishers and small-scale farmers rely on the maintenance of natural water cycles and the preservation of flowing water habitats to sustain the reproduction conditions of ichthyofauna and support their small-scale agricultural practices. On the other hand, urban consumers have a growing energy demand due to their lifestyle and expect continuous access to affordable hydroelectric power. Conflicts can arise between the survival needs of artisanal fishermen near waterbodies that have been co-opted by hydroelectric power stations for the production of energy for urban consumers [108]. The dynamic relationship among energy generation, water quality, and the livelihoods and expectations of distinct social groups calls for architectural and built environment research to address the spatial and design implications of such coexistence.

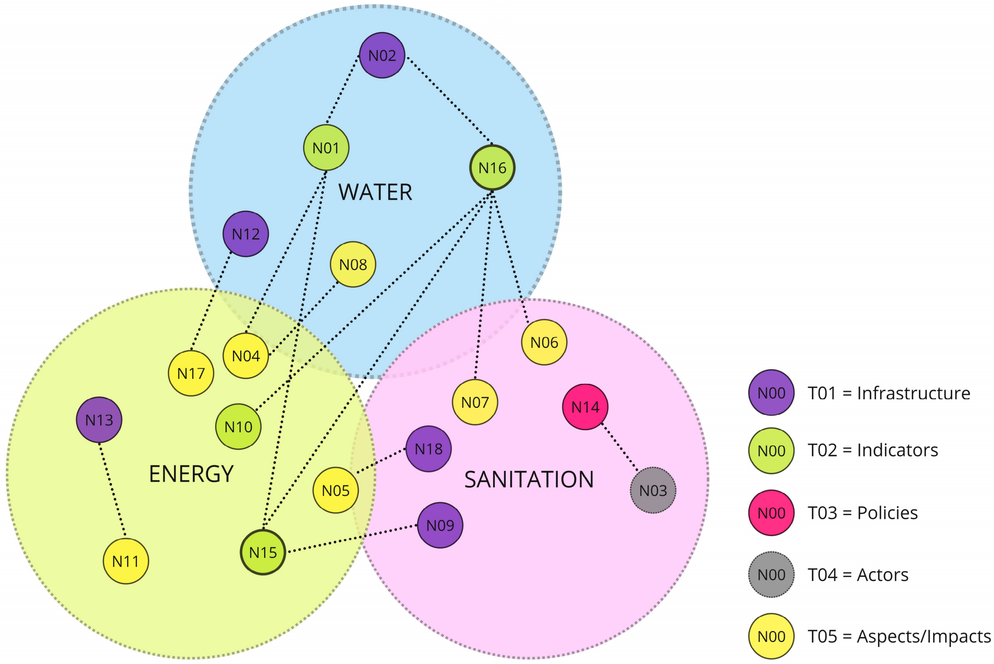

Figure 3. The WES nexus framework comprising components, nodes, and interconnections. The identified nodes include: N01: Availability; N02: Catchment; N03: Consumers; N04: Dam collapse; N05: Demands; N06: Diseases; N07: Effluent; N08: Floods; N09: Innovation; N10: Interruptions; N11: Land use; N12: Monitoring; N13: Power plants; N14: Privatization; N15: Production; N16: Quality; N17: System resilience; N18: Treatment plants.

Water levels play a crucial role in the generation of energy as well as the supply of drinking water and the functioning of transport infrastructure. However, if water levels are too high or too low, these operations can be compromised. The interconnectedness between effluent disposal (N07) in sanitation and the quality of water (N16) has even further implications for the production of power (N15) in the energy sector. Processes and events, such as the improper disposal of sewage, can contaminate water reservoirs [31,116]. Contamination can further compromise the safe operation of the system for energy and drinking water supply as a result of ecological imbalances, such as the rapid growth of algae and plants (eutrophication) [117,118].

In countries like Brazil, economic growth models often prioritize economic development over environmental quality, neglecting the needs of vulnerable populations. These populations, residing in precarious settlements, face multiple risks, including inadequate healthcare and poor environmental conditions. Our study highlights the impact of poorly planned urban growth on public health [6], manifested in the link between the quality of water (N16) and the prevalence of diseases due to poor sanitation (N06) [6,7,119]. Addressing environmental injustices through a WES nexus approach requires the involvement of specialists from various disciplines, including sanitary engineers, biologists, environmental managers, and electrical engineers.

The presented examples, such as the economic implications of a dam collapse, the geographic analysis of water catchment and availability, and the environmental science perspective on innovation in sanitation, highlight the multifaceted nature of challenges and opportunities within the WES nexus. The sociological examination of the water–energy relationship and the interconnectedness of sewage disposal and water quality underscore the importance of adopting an interdisciplinary approach to address these complex urban issues. As we move forward, it is imperative to recognize the significance of these interconnections and leverage this understanding for sustainable development.

5. Discussion and Conclusions

Unplanned or poorly planned urban growth often results in distributive inequities, with vulnerable populations facing significant challenges in accessing essential services, including water, energy, and sanitation. The failure to provide access to critical services stands in the way of progress toward the Sustainable Development Goals (SDGs) and the 2030 Agenda for Sustainable Development [31].

In this contribution, we proposed a transdisciplinary approach to the study of complex urban systems, focusing on the water–energy–sanitation nexus. Our starting point was the recognition that nexus approaches offer ways to identify and address dynamic challenges in urban systems, such as those resulting from the interplay between different sectors [1,2].

We placed the focus on Brazil, where water is central to energy generation. The common lack of appropriate sanitation infrastructure and inadequate sewage treatment and disposal pose threats to water resources and public health. The interconnected nature of water and energy highlights the need for a coordinated approach to urban planning. The failure to coordinate essential sectors, like water, energy, and sanitation, can lead to disconnected public policies. For example, the positive potential of linking energy and sanitation through the generation of energy from human waste is often overlooked. This oversight not only hampers the potential for resource synergy but also contributes to increased greenhouse gas emissions. Coordinated efforts are needed to address the interconnected systems of water, energy, and sanitation, ensuring that urban policies align with the broader goals of sustainable development [1].

We recognize the limitations of this contribution and consider it primarily an exploratory, transdisciplinary experiment. Our methodology involved transdisciplinary workshops in which participants from across different career stages and diverse disciplinary academic and professional backgrounds took part. The effectiveness of our transdisciplinary workshops could have been significantly enhanced if we had established a formal protocol and systematically recorded relevant information throughout the process. Such a structured approach would have made the subsequent analysis of both the workshop procedures and outcomes more robust and insightful.

Establishing common ground within the transdisciplinary framework proved to be a labor-intensive endeavor, aligning with the challenges inherent in such collaborative initiatives [120]. Although early career researchers were trained in systems thinking and systems mapping to facilitate the envisaged cross-disciplinary collaboration, including the generation of a scoping review and systems maps of the WES nexus, the process demanded considerable time and energy investment. Shared aims and objectives, methodological approaches, and even common terminology had to be developed and agreed upon. Furthermore, the choice of interdisciplinary scoping reviews over a systematic literature review in response to time limitations meant that an agreed protocol (including the use of specific search engines, search terms, and screening processes) was not followed, yielding results that cannot be considered comprehensive [121,122].

Although the flexibility of our proposed framework allows for adaptation to various research team needs, accommodating diverse research questions and disciplinary compositions, in hindsight, a more tailored approach, centered around concrete case studies, could have further refined its applicability and efficacy in addressing specific WES nexus challenges. A more focused and sustainable collaboration with non-academic stakeholders could have been achieved through the concentration on specific case studies. Such a targeted approach would have fostered an in-depth engagement with external partners. Notably, a case study emphasis—focused on a particular geographic context or WES nexus node—would have provided a clearer scope and objectives for the interdisciplinary literature review, ensuring a more purposeful integration of theoretical insights and practical applications.

Future research within the realm of architecture and the built environment should engage with the WES nexus. This imperative arises from the centrality of nexus components, nodes, and interconnections to the design, construction, and operation of buildings and settlements. Even the most traditional notions of architecture are directly linked to the essential infrastructures of water, energy, and sanitation. Studying how these resources and services connect to the lives and livelihoods of users can inform architectural choices and interventions across multiple levels. Although there are notable efforts to understand the architecture–environment relationship across the architectural humanities, social sciences, and engineering, these are focused on specific aspects of this relationship, and practical solutions are concerned with technical aspects of the built environment, such as energy-efficient building design. Through a better understanding of interconnections and interdependencies within the WES nexus, both scholars and practitioners can develop strategies for interventions that foster much needed sustainability and resilience in urban environments.

These reflections should not detract from the overarching argument that we sought to make in this contribution: the built environment and its entanglements with/in the WES nexus or other systems cannot be addressed through architectural (or any other type of) research and practice alone. Rather, the complex nature of urban systems requires the type of transdisciplinary collaboration that we experimented with in the research reported in this paper. This is because the very diverse disciplinary perspectives, knowledges, and research approaches can inform research design and methodology, as well as the interpretation of results. Transcending traditional disciplinary boundaries, truly transdisciplinary research is likely to be in a position to develop innovative methodological approaches that bring together unlikely methods and produce potentially surprising results in response to urgent challenges. At the heart of such research is transdisciplinary collaboration as the involvement of non-academic 'stakeholders'—the policy makers and urban practitioners tasked with decision-making processes, design and, possibly, implementation of urban (infrastructural) systems within and linked to WES and other nexuses [69,70]. This collaboration proves integral to the methods employed in this study, such as systems mapping, as it enables the formulation of questions directly pertinent to stakeholders and facilitates the rapid implementation of recommendations arising from transdisciplinary research.

We close by echoing Dovey's observation that there is an urgent need to expand into the 'enlarged professional field with a responsibility for all architectures' [32] (p. 87). Architecture remains stubbornly oblivious to its centrality to the various dimensions of human and non-human life, failing to fully mobilize the abilities afforded to it through its status as both an academic discipline and professional practice. In this context, we propose that transdisciplinary approaches—including that discussed in this paper—present a promising avenue for redefining the parameters of architectural responsibility and intervention.

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Notes

1 The notion of 'efficiency' in the context of resource use is not without critique. Scrutinizing the so-called 'techno-optimism' (the hope that technology will resolve current sustainability challenges and the climate emergency), the research shows that improvements in efficiency have not necessarily contributed to social, environmental, or economic sustainability in recent decades [55]. As Saunders and Tsao [56] argue, the 'rebound effect'—i.e., the observation that gains from improvement in efficiency are minimized by an increase in demand—should not deter scholars, practitioners, and policy makers from seeking energy improvements, as they may still contribute to a reduction in resource use.. Scholars have focused on the use of passive solar design [57–60], building-integrated photovoltaics [61–63], and other strategies to reduce the energy demand of buildings and promote the use of renewable energy.

2 Informality, as defined by UN-HABITAT [66], is the presence of multiple deprivations: the lack of access to improved water, lack of access to improved sanitation, the lack of a sufficient living area and quality/durability of structure, and the lack of security of tenure. Although they are not usually thought of as the architect's domain, the deprivations characterizing urban informality are directly related to the design, production, maintenance, and inhabitation of the built environment. Architecturally engaging with informality means, therefore, expanding into an 'enlarged professional field with a responsibility for all architectures, including those where formal outcomes are uncertain and where makeshift forms play important roles' [32]. The entanglement of the built form, environmental systems, economic structures, and social relations suggests the transgression of 'normalised boundaries of architectural practice and ideology' [32]. This requires the application of systems thinking to introduce new perspectives on seemingly familiar phenomena in architectural and urban research [10,67].

3 By transdisciplinary, we mean a process of knowledge production that acknowledges multiple ways of experiencing, studying, and understanding the world and that includes non-academic stakeholders [69–71].

4 The geographical focus of the workshop was the Tietê River Basin in São Paulo, Brazil.

5 A common application within systems mapping is causal loop diagraming, a qualitative method portraying causal relationships between elements. These connections can be either positive or negative [77]. Causal loop diagraming enables researchers to integrate diverse stakeholder perspectives and to capture emergent dynamics that a linear approach might overlook.

6 In the context of architectural education, practice, and research, systemic diagraming—a type of systems mapping—is a method to encourage architects to engage with issues beyond the immediate building site or master plan [10]. Borrowed from the natural sciences, systemic diagraming provides a tool to map and communicate actors, resources, and flows within a system, allowing for a nuanced understanding of the interconnections at various scales. Systemic diagraming can be employed to map relationships and to assess the potential consequences of proposed interventions. This enables architects to address complex conditions and understand the broader implications of their interventions on political, socio-economic, and environmental dimensions. The spatial scale emerges as a practical self-regulation mechanism, allowing architects to understand smaller systems within the broader context of a given site.

7 These nodes are representative of the disciplinary backgrounds of the workshop participants and may vary with the set up of a multi-disciplinary team.

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